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PI: Martin A. Gundersen – University of Southern California
Co-PI: James Dickens – Texas Tech University
Co-PI: William Nunnally – University of Missouri-Columbia

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

University of Southern California
Electrical Engineering-Electrophysics
3737 Watt Way, PHE 512
Los Angeles, CA 90089-0271

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
USAF, AFRL
Air Force Office of Scientific Research
4015 Wilson Blvd, Room 713
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14. ABSTRACT

The desire to move high energy pulsed power systems from the laboratory to practical field systems has led to the establishment of the FY2001 Multidisciplinary University Research Initiative (MURI) on Compact, Portable, Pulsed Power (CP^3). The University of New Mexico and the University of Southern California each lead a consortium of universities to address the fundamental issues critical to improved compact pulsed power. This report describes progress on this program by the University of Southern California lead consortium. Results are presented in the following key thematic areas: Gas phase and opening switches, increased energy density storage using liquid dielectrics, solid-state and optical switching. New results include advanced switches for repetitive pulsed power and innovative pulse generator (PG) design. Specific topics addressed are: Blumlein transmission lines, liquid breakdown in oil, water and propylene carbonate, pseudospark and Back-Lighted Thyratron (BLT) switches, compact pulsers, and high power solid-state switches. Applications that are emerging from this program include innovation in Blumlein architecture for HPM, Marx PGs for HPM, pseudospark PGs for AF jet ignition, ultra-compact PG for AF biological applications, and advanced PGs for cathode research for HPM.

15. SUBJECT TERMS
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"Compact, Portable Pulsed Power"

AFOSR Grant No. F49620-01-0387

M. Gundersen, P.I. mag@usc.edu

I. INTRODUCTION

The desire to move high energy pulsed power systems from the laboratory to practical field systems has led to the establishment of the FY2001 Multidisciplinary University Research Initiative (MURI) on Compact, Portable, Pulsed Power (CP^3). The University of New Mexico and the University of Southern California each lead a consortium of universities to address the fundamental issues critical to improved compact pulsed power. This report describes progress on this program by the University of Southern California lead consortium. Results are presented in the following key thematic areas: Gas phase and opening switches, increased energy density storage using liquid dielectrics, and solid-state and optical switching. New results include advanced, compact switches for repetitive pulsed power and innovative pulse generator (PG) design. Specific topics addressed are: Blumlein transmission lines, liquid breakdown in oil, water and propylene carbonate, pseudospark and Back-Lighted Thyratron (BLT) switches, compact pulsers, and high power solid-state switches. Applications that are emerging from this program include innovation in Blumlein architecture for HPM, small BLT switches for HPM, pseudospark PGs for AF jet ignition, ultra-compact PG for AF biological applications, and advanced PGs for cathode research for HPM.

II. GAS PHASE AND OPENING SWITCHES

OBJECTIVES

The objectives of the program are:

- Resolve key scientific issues related to development of robust compact pulsed power with high voltage output.
- Understand super-emissive cathode switches through simulations and physics experiments.
- Investigate advanced semiconductor fabrication techniques for high energy-density capacitors.
- Determine the fundamental breakdown mechanism of liquids (before bubble or streamer formation).
- Involve the community of scholars and scientists in solving the technical issues.
- Test and demonstrate innovations in pulsed power design.

STATUS OF EFFORT

Our research program concentrates on an essential and difficult part of the compact pulse power project – the demonstration of pseudospark switch as an enabling technology in real applications and the extension and optimization of this technology to not-yet commercial pseudospark or Back-Lighted-Thyratron (BLT) switches with much smaller volume and much higher voltage operation.

We have developed a robust pulse generator based on the FS2000 commercial pseudospark switch built by ALSTOM in Germany. This company has since stopped production of the FS2000 and now there are no commercial pseudospark switches available anywhere. We have used this pseudospark pulse generator successfully in experiments on transient plasma

ignition of combustion for several years. It has been an indispensable aid in the following collaborative experiments: igniting a Pulse Detonation Engine with Naval Postgraduate School in Monterey, CA, performing pulsed plasma experiments at Wright-Patterson AFRL, performing optical combustion diagnostic experiments at Stanford, performing combustion experiments at Caltech similar to those performed at Stanford, and performing combustion control experiments at the University of Cincinnati. Another FS2000-based pulse generator was modified for longer pulses and lower output impedance to be used in carbon fiber field emission cathode experiments in collaboration with Naval Postgraduate School in Monterey. A related effort used three FS2000 commercial pseudospark switches in a Marx generator. In order to facilitate the combustion experiments, several versions of the line type pulse generator were constructed using the FS2000 pseudospark switches from the Marx generator assembly that was disassembled at the end of its demonstration life, as no new commercial pseudospark switches could now be obtained.

A fully solid-state, long-life, compact pulse generator was developed and built to extend the transient plasma ignition experiments to shorter pulse regime. A novel two-pulse architecture has been developed in which the transient plasma load is employed as a final switch, removing the high energy requirement from the fast, 20ns, 60kV pulse generator by adding this fast pulse to a slow, 30kV pulse which is below the threshold for significant corona emission. This scheme is presently being explored with the goal of significantly increasing the efficiency through energy-recovery circuits.

Several ultra-compact, solid-state switching pulse generators have been designed and constructed for real time biological cell electro-perturbation experiments, similar in design to the solid-state ignition pulsers. These generators use magnetic pulse compression in combination with low-cost rectifiers as opening switches. The primary focus of the development effort concentrated on decreasing the size and weight while increasing the reliability and life, both of which are essential criteria for practical deployment in application.

Continuing the development of pseudospark switches for reliable and long-life operation, optically triggered versions (BLT) of small size were constructed and successfully operated. Several intermediate size switches were constructed and tested. The size-dependence of voltage hold-off and trigger stability were studied. The results suggested that the smaller switch is more reliable and has a higher hold-off voltage due to the smaller stressed electrode area. Further results from these systems were reported at the 2006 Power Modulator Conference in Washington, D.C. Studies of transient plasma ignition of Pulse Detonation Engines using the reduced size high repetition rate pseudospark pulse generator were used in further successful experiments on flowing mixtures with significant repetition rates in collaboration with Dr. C. Brophy and Dr. J. Sinibaldi at the Naval Postgraduate School Laboratory in Monterey, CA. and in similar experiments at the Wright-Patterson AFRL in Dayton, OH.

ACCOMPLISHMENTS/NEW FINDINGS

The idea of replacing the charging resistor chain in a pseudospark Marx generator with HV diodes was simulated with MOSFET switches. The MOSFET Marx generator was tested successfully and has since been redesigned for higher voltage and higher repetition rate in order to serve in biological cell electro-perturbation experiments.

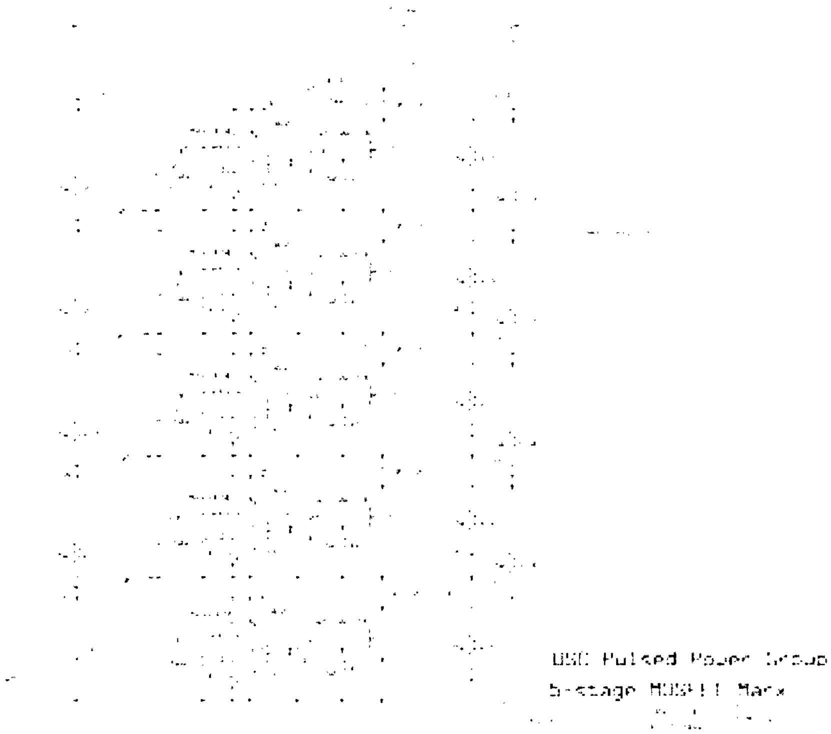


Figure 1. The five-stage diode-chain isolated MOSFET Marx generator circuit.

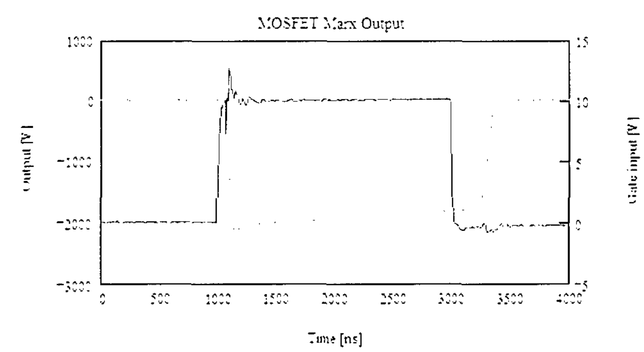


Figure 2. The output of the first two stages of the MOSFET Marx generator.

Development of the pseudospark-based pulse generators continued with incremental improvements in diverse circuitry. For example, the pseudospark trigger suffered from intermittent failure due to the sensitive MOSFETs used in the circuit. The trigger circuit has since been redesigned with robust SCRs replacing the fragile MOSFETs.

Studies of small pseudosparks and back-lighted thyratron (BLT) switches, operating with currents >7 kA, and hold off >40 kV, were conducted for the purpose of further development of compact and light weight pulse generators. Two different size switches were studied. The switches were operated in an optically triggered mode (BLT), both with helium and with hydrogen fill, at a repetition rate of 10 Hz. A 355 nm laser and a small flashlamp were used as optical triggers. The 10 mJ laser trigger resulted in small, 50 ns delay and small, ~4 ns jitter, while the much smaller, few mJ energy from the flashlamp resulted in ~5 μs delay and correspondingly large ~1 μs jitter. Operation in electrically triggered pseudospark mode was conducted as well, using a thin trigger wire.

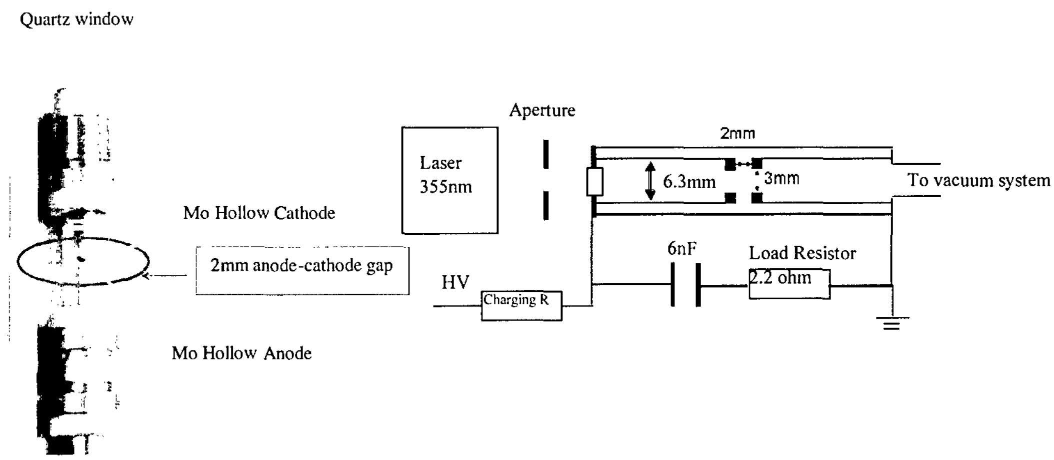


Figure 3. The smallest compact optically triggered BLT switch and the test set-up.

The inside structure of the mini-BLT and the medium-BLT is similar. The mini BLT electrodes are made of 3 mm thick molybdenum disks with a 3 mm central hole, capped on a hollow OFHC 1/4" diameter copper tube. In the medium-BLT, 15 mm molybdenum discs with 3mm central holes are inserted into 3/4" diameter OFHC copper tubes. 2mm electrode gaps are maintained in both the mini-BLT and the medium-BLT.

Fig. 4 shows the operation of the optically triggered mini-BLT in 800 mtorr Helium. The initial charge of the 6nF capacitor was 27 kV. 43 ns wide, 15.6 kV amplitude pulse is generated on the 2.2 Ohm load resistor. The fall time of the current is 19 ns and the pulse width of the current is 38ns. Peak current is 6.7 kA and dI/dt is 3.5_10^{11} A/s. The transferred charge per pulse is 0.25 mC. Over 9 kA peak current was observed when the capacitance was increased to 15 nF and the charging voltage was raised to 28KV. The pulse shape, and thus, the peak current, was limited only by the circuit inductance. The gas pressure, gas type and trigger energy did not affect the rise-time, pulse width or peak current.

The hold-off voltage depended strongly on the switch size. The larger switch had significantly lower hold-off voltage in both Helium and Hydrogen, and had a higher rate of misfire at comparable anode voltages than the small switch.

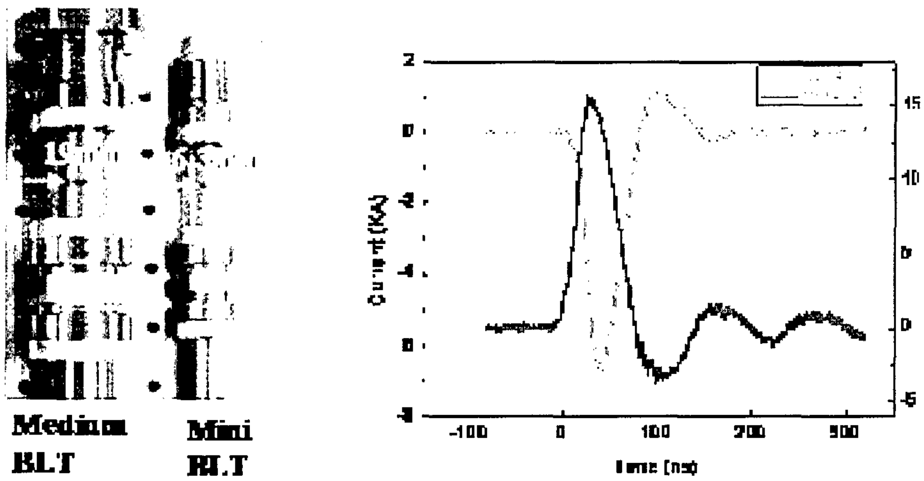


Figure 4. The two BLT switches studied and the pulse output of the smaller switch

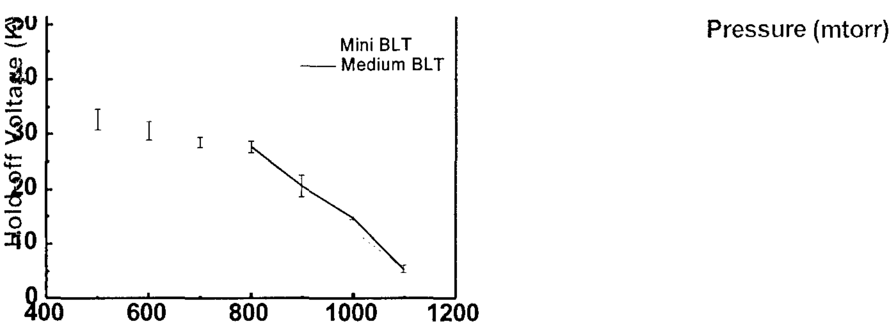


Figure 5. Voltage hold-off for the two different size switches in He and in H_2.

There are several possible explanations for the size dependence of the hold-off voltage. The larger electrode surface under HV stress presents more defects, such as contamination and micro-protrusions that contribute for the earlier breakdown in the medium-BLT.

Over 45KV hold-off voltage was achieved by the mini-BLT under 800mtorr Helium pressure after proper conditioning. Higher hold-off voltage, up to ~50 kV, is expected to be achieved at lower gas pressure as demonstrated by earlier research on BLTs.

The small BLT switch was successfully integrated into lumped-element Blumlein architecture (output to approx. 60 kV) with a transient plasma chamber as load. These studies suggest that the small pseudospark/BLT is a potential pathway towards ultra compact superemissive cathode-based switches for compact repetitive pulsed power applications.

In the quest to further reduce size and weight of the HV pulse generators, fully solid-state long-life circuits, using magnetic pulse compression, were designed and constructed. The

pulse generators are designed to create 20 ns FWHM, 60 kV amplitude pulses into 200-ohm load. The generators consist of an IGBT or MOSFET switched resonant charging circuit, two steps of magnetic pulse compression, and a semiconductor opening switch (SOS) using low cost mass-produced automotive rectifier diodes. This approach follows the evolution of progressively more compact pulse generators constructed in our laboratory from thyratron switch-based to pseudospark or BLT-based, and finally, diode opening switch-based systems, generating similar amplitude but progressively shorter HV pulses, as shown in Figure 6.

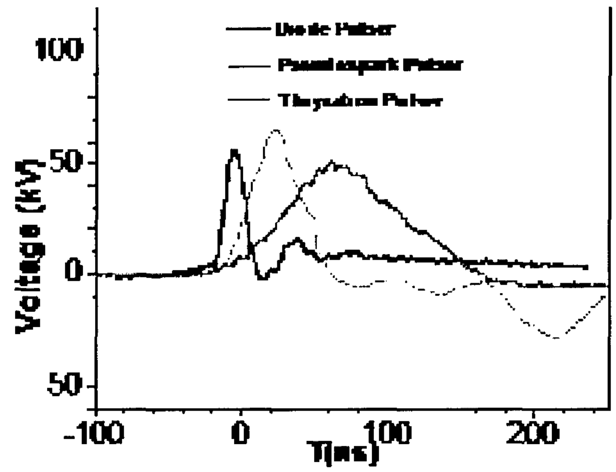


Figure 6. The evolution of short-pulse HV pulse generators

The size and weight of the magnetic compression stages depend strongly on the pulse energy passing through the cores. We have developed a novel concept wherein the load – a combustion chamber or an e-beam cathode - is used as a high energy switch, significantly reducing the energy required in the short pulse. It is a dual pulse system, where a slow, 3-5 us long, 30 kV pulse is applied to the e-beam cathode first. The voltage of this slow pulse is insufficient for field emission. At the peak of this voltage pulse a second, fast, 20 ns, 30 kV pulse is added to the first pulse and the combined voltage of ~90 kV then results in e-beam generation. The main energy is in the slow pulse, not requiring pulse compression, so the size and expense of the magnetic cores can be significantly reduced. The dual-pulse generator was designed and constructed and tests were successfully conducted, as applied to the transient plasma ignition experiment. The idea of this dual-pulse system is shown in Figure 7.

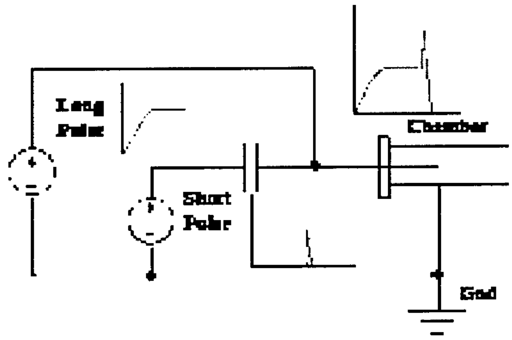


Figure 7. Illustration of the dual-pulse idea.

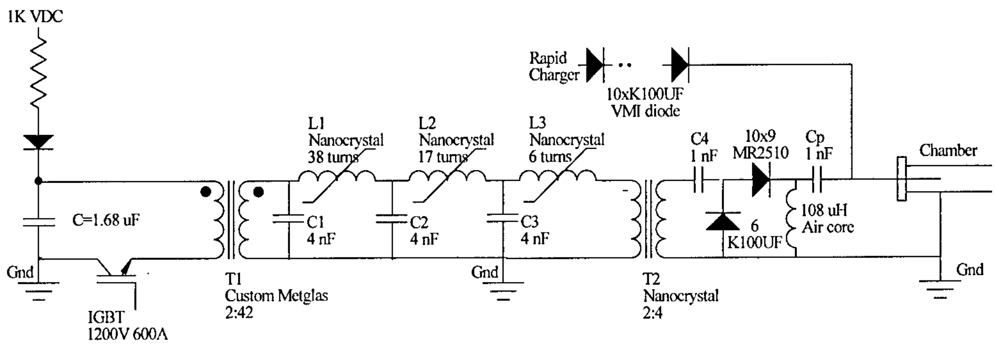


Figure 8. Circuit schematic of the 90 kV dual-pulse solid-state pulse generator.

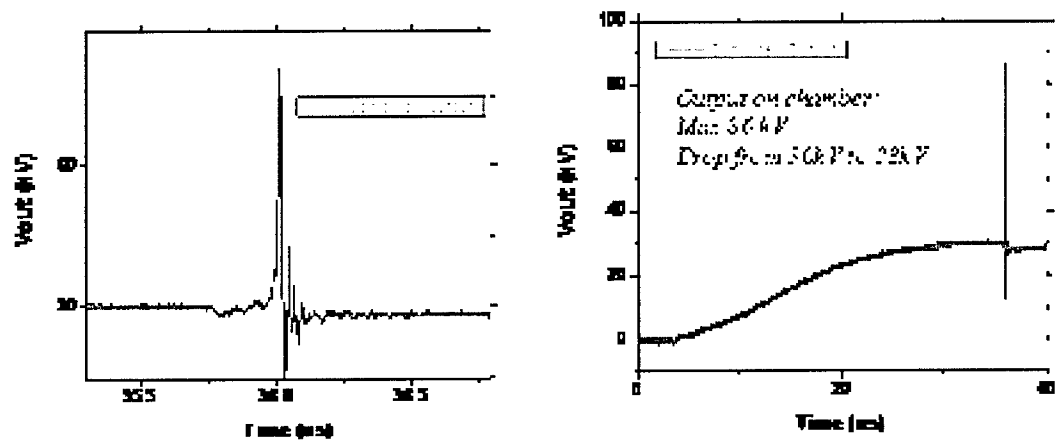


Figure 9. The dual pulse generator output voltage.

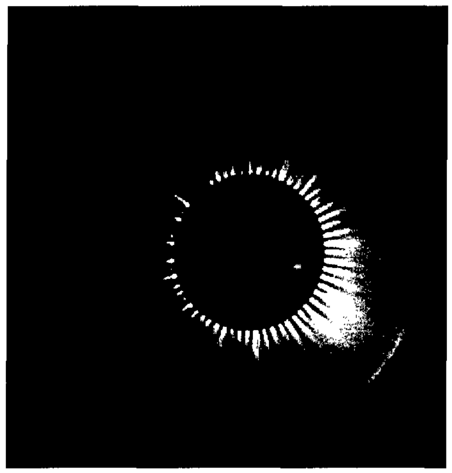


Figure 10. The streamers formed in atmospheric pressure air by the 20 ns, 90 kV pulse.

Development of the diode-based pulse generators have been extended both to higher voltage (60 kv) and to higher current, ~1kA, although not simultaneously. A diode-based nanosecond pulse generator has been designed and constructed which delivers 5 ns wide, 7.2 kV pulses at 5 kHz repetition rate into a 10 ohm load.

Stacked Blumlein systems

The University of Missouri – Columbia (UMC) investigated and developed the basis for fielding the most compact pulse power system. The most compact pulse power system architecture is one in which the energy to be delivered to the load is stored in the system during the interpulse period and a large fraction of the pulse energy is transferred to the load during the pulse period. UMC determined that the Stacked Blumlein Line (SBL) system is such architecture and that it is feasible to deliver approximately 30 to 50 percent of the energy stored in the dielectric to the load when the auxiliary systems are included in the system volume. The SBL system approaches the most efficient pulse power system in that an SBL system can be designed to deliver a specific pulse voltage, a specific pulse current and a specific pulse length by adjusting the system dimensions. Furthermore, the SBL system can be designed with a specific output impedance so that the source impedance can be matched to the load impedance for maximum power transfer.

The UMC work further identified the critical components for minimum volume pulse power system. Specifically, the SBL stage switches and the dielectric energy storage material are presently the critical components for implementation of these systems. The presently available dielectrics for energy storage have sufficient dielectric strength and sufficiently large relative permittivity to store energy in excess of the capability of the available switches. Therefore, the stage switches are the most critical element of an SBL system. The UMC work further defined the required parameters of these critical SBL switches, including high voltage, high current, low inductance, low resistance transition time and precise control. A desirable requirement is the ability to control the switches optically due to the high voltages at which the switches operate.

UMC work identified two types of switches with the potential to serve in the SBL applications, specifically, Photo Conductive Semiconductor (PCS) switches and Pseudo Spark Gas (PSG) discharge switches. Two system designs were completed using the switch candidates above for Air Force applications. The PS switches, designed and demonstrated at

USC, were found to be the optimal switches for long pulse power systems that power narrow band microwave sources (500 kV, 1 kA, 1 ms pulse). PCS switches were found to be the viable candidate for ultra-wide band pulse generation (500 kV, 10 kA, ~50 ns pulse). The PCS switches can be closed with a smaller resistive phase times and lower inductance, but with shorter conductive time than the PSG switches, while the PSG switches have longer closure times, higher inductance, but conduct higher currents for longer periods of time. The PSG SBL system was designed with a system energy density 50 percent of the energy density of the energy storage dielectric while the PCS SBL system was designed with a system energy density 30 percent of the energy density in the dielectric.

UMC further innovated and demonstrated the first operation of a semi-insulating, extrinsic, SiC photo conductive switch, identified two types of semiconductor band gap compensation structures using Vanadium, demonstrated the operation of an extrinsic photo-conductive SiC switch at two wavelengths, demonstrated that the conduction area can be increased using extrinsic photo conductivity, and demonstrated the first high voltage, high current, thermal management package of a PCS switch.

ACCOMPLISHMENTS/NEW FINDINGS

The following list documents specific results and accomplishments of the University of Missouri – Columbia contribution to the USC MURI on Compact Pulse Power Systems.

1. Identified most compact pulse power system architecture
    a. Stacked Blumlein Line (SBL)
2. Identified Critical components necessary for SBL implementation
    a. Stage Switches
        i. low inductance, fast resistive transition time closure
        ii. high voltage, high current
        iii. precise temporal closure control -- Optical coupling
    b. Photo-Switches or Mini – BLT (Pseudo spark)
        i. Optical closure control with low jitter
        ii. High voltage, high current
        iii. Low inductance
        iv. Low resistive transition times
    c. High Energy Density, Castable Dielectrics
3. Designed long and short pulse SBL systems:
    a. Developed simple design method for SBL systems
    b. First designs indicate system energy density ~ 33 % of dielectric energy density
4. Demonstrated first extrinsic, semi-insulating SiC photo conductive switch
    a. Identified two types of compensation structures
    b. Designed, fabricated, and operated first Semi Insulating, SiC high voltage switch
        i. ~ 0.5 square cm
        ii. SiC dielectric strength 300 kV/cm
        iii. Operated switch with two wavelengths
        iv. Operated in Linear Extrinsic operational mode
    c. Identified new concepts for fabrication and operation
        i. Methods of increasing blocking voltage
        ii. Methods of designing recombination time
5. Developed first extrinsic, photo-conductive high voltage, high current, high thermal conductivity switch package
    a. Identified failure regions

b. Developed method of using high permittivity materials in tailoring electric field in electrode – SiC interface.

Stacked-Blumlein Line System

The function of the ideal pulsed power system is embodied in the Stacked Blumlein Line (SBL) Generator illustrated in Fig. 11.

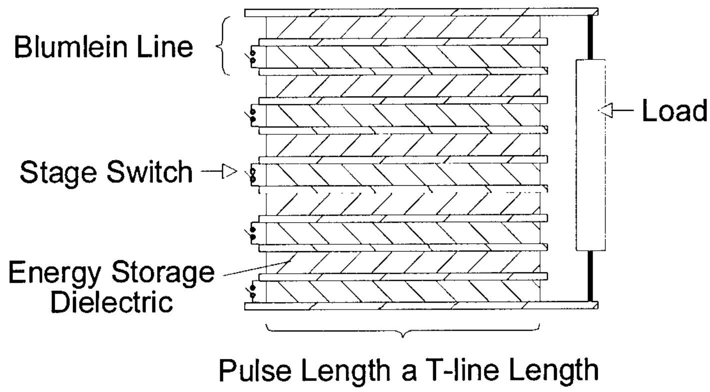


Figure 11. Stacked Blumlein Line Power System

The output voltage of a Blumlein Line is equal to the charge voltage when the Blumlein output impedance is matched to the load impedance. The SBL output voltage is scaled by adding another Blumlein line to the stack. The load current is scaled by designing the width of the plate conductor transmission line sections of the Blumlein line to match the desired current. The pulse length of the SBL system is scaled by the length of the transmission line sections of each Blumlein line. Finally, the shaping of the load pulse is determined by the length of the transmission lines and the characteristics of the switch closure associated with each Blumlein line in the stack.

The effect of the geometry on switch inductance as a function of multiple, parallel conduction paths is plotted in Fig. 12. The ideal situation is one in which current through the switch is uniform across the width of the transmission line.

In summary, the stage switches used in the most compact of pulse power system architectures must have a low inductance, a very small resistive transition time, very small relative closure times or jitter, and handle high voltages and high currents. These specific values of the switch parameters are related to the load impedance and the desired pulse risetime and thus related to the pulse line impedance as illustrated in TABLE 1.

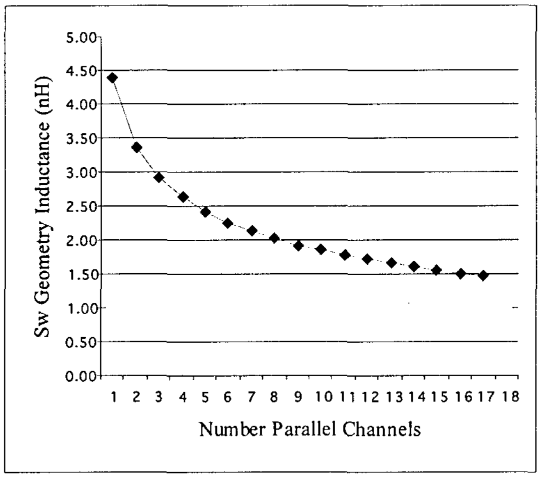


Figure 12. Inductance vs. Parallel Current Channels

TABLE 1: SBL Stage Switch Requirements

Parameter	Value Equation
SBL Design	
Load Impedance	Z_L
Load Voltage	V_L
Load Current	$I_L = V_L/Z_L$
Pulse Risetime	T_{rise}
SBL Output Impedance	$Z_B = Z_L$
Blumlein Stage Voltage	V_S
Number of Series Blumleins in SBL	$N_B = V_L/V_S$
Blumlein Stage Impedance	$Z_S = Z_B/N_B$
Stage Switch Parameters	
Switch inductance	$L_S < (T_{rise} Z_S)/10$
Switch Resistive Transition time	$T_{rise}/10$
Switch voltage	V_S
Switch Current	$2I_L$
Switch Closure variation (Jitter)	$T_J = T_{rise}/20$

"Compact, Portable Pulsed Power"

III. LIQUID DIELECTRIC

OBJECTIVES

Since the beginnings of pulsed power, liquids have played a central role as dielectric material in energy storage, pulse forming, and switching. The latter utilizes liquid breakdown at high fields, thus going beyond just the insulating property of liquids. However, in most cases (energy storage, pulse forming) breakdown is detrimental to the proper functioning of a pulsed power system. It is also obvious that the size of a pulsed power system has always been a concern, and the effort of making existing systems even more compact will have to deal with the higher electric fields that come with the inherently smaller distances of a compact system.

Though an abundance of experimental data is available for breakdown in various insulating liquids, such as water, cyclohexane, and the noble gases, the basic physics of liquid breakdown has remained unclear. The two classic physical models are the crack propagation, which was recently transferred from solid breakdown, and the older bubble mechanism. It is the objective of this experimental investigation to further our understanding of liquid breakdown on a nanosecond timescale, thus paving the way to developing breakdown models with *a-priori* prediction capabilities.

STATUS OF EFFORT

Two manuscripts have been generated in 2006 that describe the progress in research effort (one conference contribution, one manuscript accepted, one submitted waiting for review). Another graduate student, who was 100% supported by this MURI, has received his PhD in 2006.

The past year's efforts have been focused on identifying and quantifying the differences between cathode initiated and anode initiated breakdown. Many researchers have observed differences between these two breakdown processes, but in the past year, an effort has been made in identifying the physical mechanisms between the two. Several experiments have also been conducted in which the conditions of breakdown are "artificially" (i.e. pressure, temperature, etc.) enhanced for one process or the other to show exaggerated changes in breakdown process.

ACCOMPLISHMENTS/NEW FINDINGS

A summary of the experimental results for each experiment is shown below in the following figures. Figure 1 illustrates the dependence of pressure on breakdown voltage. The negative needle (Blue) shows a strong dependence on pressure while the positive needle

case (Red) shows little or no dependence on pressure. This helps support the theory of bubble formation for cathode initiated breakdown and an electronic process for anode initiated breakdown.

Figure 2 is more qualitative and shows high speed images of shadowgraphy with overlaid luminosity of DC Breakdown in Univolt 60 oil for positive and negative needles. Important observations to make in these images is the general shape of the breakdown channels for both breakdowns (cathode initiated is "bushy" and has less branching, while the anode is narrow and has more branching). More interesting is the increased light emission from the cathode initiated breakdown. In contrast, the total light output of the anode initiated breakdown is many times less.

The final two graphs shown in Figure 3A&B show the time-to-breakdown for pulsed voltage application of positive and negative needles at atmosphere and partial vacuum. Again, the data shows a strong dependence on pressure for the cathode initiated breakdown and little dependence for the anode initiated breakdown.

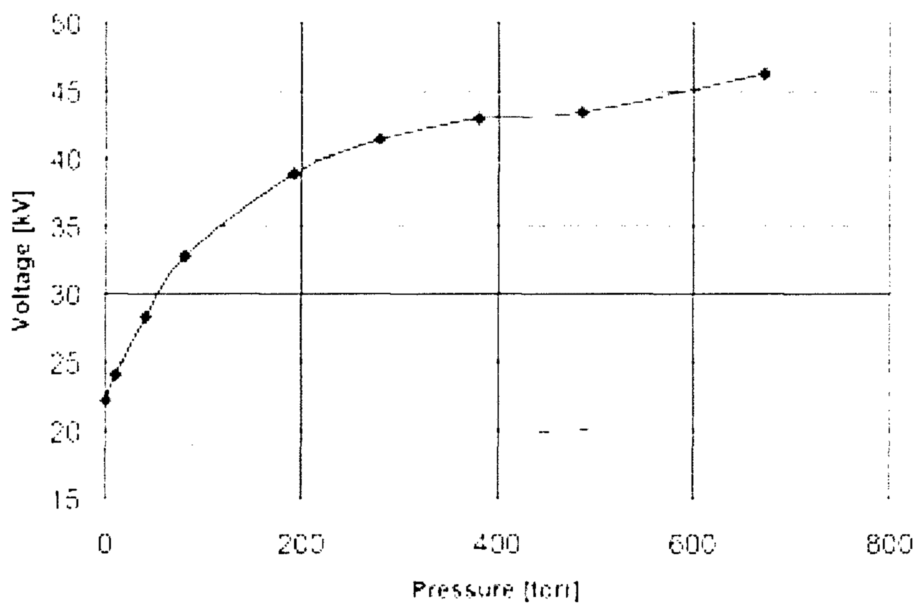


Figure 1 Breakdown voltage vs pressure for Positive (Red) and Negative (Blue) Needle in Univolt 60 Oil

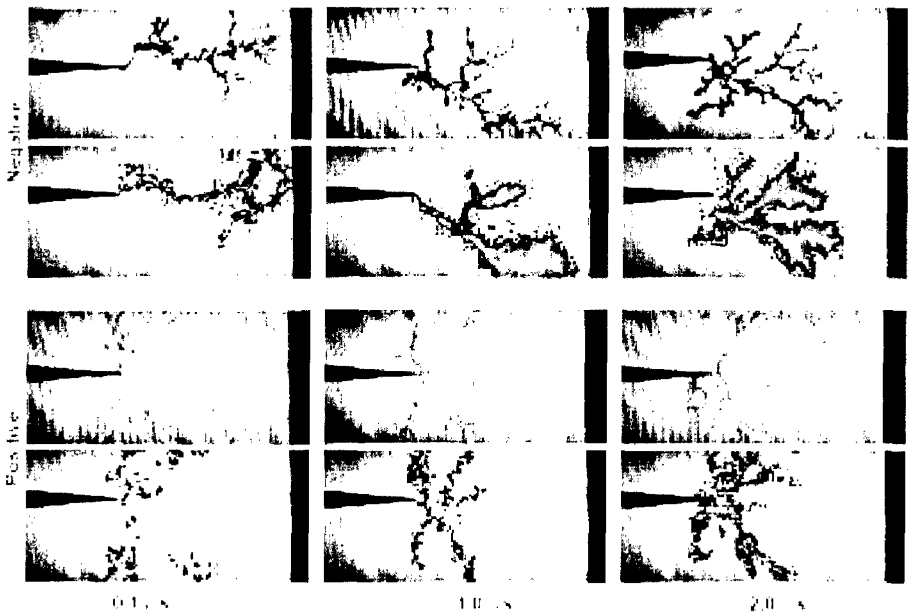
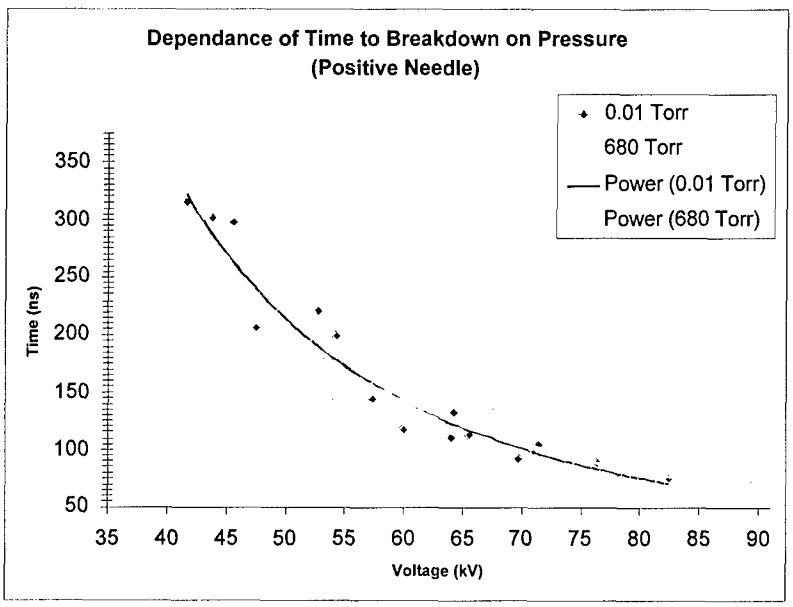
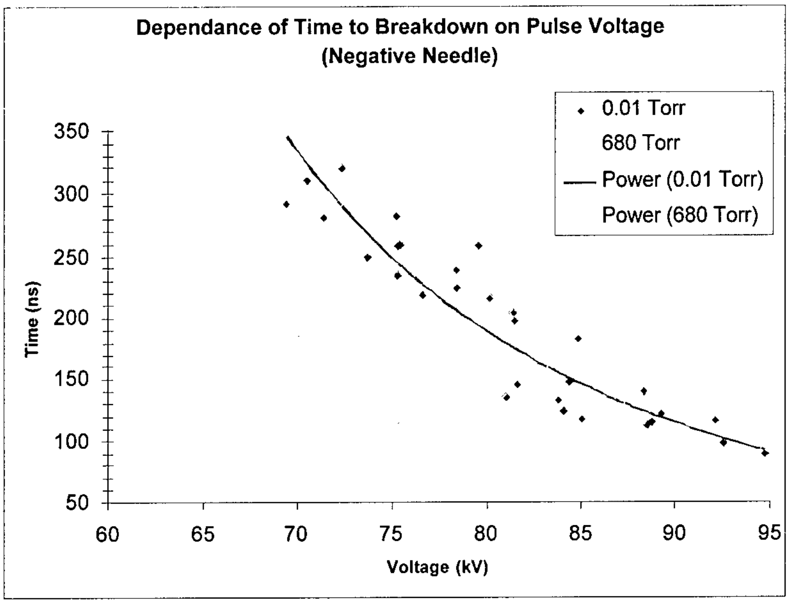


Figure 2. Shadowgraphy and Overlaid Luminosity – of DC Breakdown in Univolt 60 Oil for Positive and Negative Needles.



A)



B)

Figure 3. Dependence of Time to Breakdown for Positive and Negative Needle

IV. PERSONNEL, PUBLICATIONS AND AWARDS

PERSONNEL SUPPORTED

University of Southern California

Professor Martin Gundersen	Professor, Consortium PI
Dr. Andras Kuthi	Research Scientist
Dr. P.T. Vernier	Research Scientist/Engineering Manager
Dr. Chunqi Jiang	Postdoctoral Research Associate
Ms. Kathy Gu	Graduate Research Assistant
Ms. Shui Qiong	Graduate Research Assistant
Mr. Fei Wang	Graduate Research Assistant
Ms. Mya Thu	Graduate Research Assistant
Mr. Charles Cathey	Graduate Research Assistant
Mr. Tao Tang	Graduate Research Assistant
Ms. Hao Chen	Graduate Research Assistant
Mr. Meng-Tse Chen	Graduate Research Assistant

Texas Tech University

Professor James Dickens	Associate Professor
Professor Hermann Krompholz	Professor
Professor Andreas Neuber	Associate Professor
Professor Charles Myles	Professor of Physics
Mr. Mic Cevallos	Ph.D. student
Mr. Michael Butcher	Ph.D. student

University of Missouri – Columbia

William C. Nunnally	Professor
Naz Islam	
Kapil Kelkar	
Chris Fessler	

PUBLICATIONS

University of Southern California

A. Journal Papers

B. Papers in Conference Proceedings

1. T. Tang, A. Kuthi, F. Wang and M.A. Gundersen, "Design of 60kV 20ns solid state Pulse generator Based on magnetic reactor driven diode opening switch," 27th International Power Modulator Conference 2006, Washington, D.C., May 14-18th, 2006.

2. F. Wang, C. Cathey, A. Kuthi, T. Tang, H. Chen, and M.A. Gundersen, "Pseudospark-based power modulator technology for transient plasma ignition," 27th International Power Modulator Conference 2006, Washington, D.C., May 14-18th, 2006.

3. H. Chen, A. Kuthi, C. Jiang and M.A. Gundersen, "High Voltage, Small Back-Lighted Thyratrons," 27th International Power Modulator Conference 2006, Washington, D.C., May 14-18th, 2006.

4. H. Chen, C. Jiang, A. Kuthi, and M.A. Gundersen, "Small Size Back Lighted Thyraton," EAPPC 2006, Chengdu, China, September 18-22, 2006.

INTERACTIONS/TRANSITIONS

A. PARTICIPATION/PRESENTATIONS AT MEETINGS, CONFERENCES, SEMINARS, ETC.

In addition to the above presentations, Ms. Hao Chen and Mr. Tao Tang, graduate students working on the project, as well as the involved faculty, attended the 2006 IEEE International Power Modulator Conference, May 14-18, Washington, D.C. Each student gave an oral presentation on the work specifically done under this MURI. Their work was discussed with students, faculty from other universities, and research laboratories.

B. CONSULTATIVE AND ADVISORY FUNCTIONS TO OTHER LABORATORIES AND AGENCIES

C. TRANSITIONS. DESCRIBE CASES WHERE KNOWLEDGE RESULTING FROM YOUR EFFORT IS USED, IN A TECHNOLOGY APPLICATION.

INTERACTIONS WITH AFRL LABORATORY RESEARCHERS

Research at USC has included the application of transient plasma science to the ignition of pulse detonation engines (PDE). Compact, portable pulsed power research has been the key to the results that have been achieved, and to this technology generally. This is because

a short (typ. 30 to 100 ns), high voltage (typ. 30 to 70 kV), fast rising pulse is required for implementation. The best available means of accomplishing this is through the use of pseudospark-based pulse generators, because the pseudospark enables a faster-rising pulse than traditional approaches using thyratrons, and also allows long-term reliable operation relative to technologies based on spark gaps.

In studies of transient plasma ignition, the pseudospark-based pulse generators have been used for several DoD experiments. Initial studies were conducted at WPAFRL in collaboration between USC (C. Cathey, M.G.) and Dr. F. Schauer's PDE research group. Tentatively, a factor of two (2) reduction in delay was observed in AvGas, which addresses a central issue for PDE repetition rate. Improved lean-burn operation was also achieved.

Dr. Gundersen and his group are collaborating with Drs. Williams, Carter and Busby on the pulsed power implementation for other combustion experiments that will investigate pulsed plasma effects.

The pseudospark-based pulse generators were used for several tests of transient plasma ignition with the PDE at the Naval Postgraduate School (NPS) (Drs. Brophy, Sinibaldi and Netzer). In a review for the Office of Naval Research, Dr. Brophy reported that the transient plasma igntion method was "enabling", and that this would be the key for their ignition methodologies for future work on PDE. The success achieved at NPS included achieving a new level for repetition rate operation with high flow. Considerable interest was expressed by industrial participants including GE Global Research, Volvo, and Pratt and Whitney.

Texas Tech University

A. Journal Papers

1. M. Cevallos, M. Butcher, J. Dickens, A. Neuber, and H. Krompholz, "Imaging of Negative Polarity DC Breakdown Streamer Expansion in Transformer Oil due to Variations in Background Pressure," IEEE Transactions on Plasma Science, vol. 33, 494-495, 2005.

2. M. Butcher, A. Neuber, M. Cevallos, J. Dickens, and H. Krompholz, "Conduction and Breakdown Mechanisms in Transformer Oil", IEEE Transactions on Plasma Science, Volume 34, Issue 2, Part 3, 467 – 475, April 2006.

3. J. Qian, R. P. Joshi, J. Kolb, K. H. Schoenbach, J. Dickens, A. Neuber, M. Butcher, M. Cevallos, H. Krompholz, E. Schamiloglu, and J. Gaudet, "Microbubble-based model analysis of liquid breakdown initiation by a submicrosecond pulse," J. Appl. Phys. 97, 113304, 2005.

4. M. Cevallos, M. Butcher, J. Dickens, A. Neuber, and H. Krompholz, "Bubble Dynamics and Channel Formation for Cathode Initiated Discharges in Transformer Oil," In Review.

5. M. Cevallos, M. Butcher, J. Dickens, A. Neuber, and H. Krompholz, "Composite Shadowgraphy and Luminosity Images of Self Breakdown Discharge Channels in Transformer Oil," submitted to IEEE Transactions (Feb 2006)

B. Papers in Conference Proceedings

1. M.D. Cevallos, M.D. Butcher, J.C. Dickens, A.A. Neuber, and H.G. Krompholz, "Bubble Dynamics and Channel Formation for Cathode Initiated Discharges in

Transformer Oil," to be published in *Proceedings of the 15th Int. IEEE Pulsed Power Conference*, Monterey, CA, 13-17 June 2005.

2. J. Qian, R.P. Joshi, J.F. Kolb, K.H. Schoenbach, J. Dickens, A. Neuber, M. Butcher, M. Cevallos, H. Krompholz, E. Schamiloglu, and J. Gaudet, "Simulation Studies of Liquid Water Breakdown by a Sub-Microsecond Pulse," to be published in *Proceedings of the 15th Int. IEEE Pulsed Power Conference*, Monterey, CA, 13-17 June 2005.

3. M.D. Cevallos, M.D. Butcher, J.C. Dickens, A.A. Neuber, and H.G. Krompholz, "Composite Shadowgraphy and Luminosity Images of Self Breakdown Discharge Channels in Transformer Oil," to be published in *Proceedings of the 15th Int. IEEE Pulsed Power Conference*, Monterey, CA, 13-17 June 2005.

4. M. Butcher, M. Cevallos, A. Neuber, H. Krompholz, and J. Dickens, "Investigation of Charge Conduction and Self-Breakdown in Transformer Oil," to be published in *Proceedings of the 15th Int. IEEE Pulsed Power Conference*, Monterey, CA, 13-17 June 2005.

5. J. Dickens, A. Neuber, and M. Kristiansen, "Pulsed and DC Breakdown in Liquids," to be published in *Proceedings of The First Euro-Asian Pulsed Power Conference*, 18-22 September 2006.

C. Presentations

1. M.D. Cevallos, M.D. Butcher, J.C. Dickens, A.A. Neuber, and H.G. Krompholz, "Bubble Dynamics and Channel Formation for Cathode Initiated Discharges in Transformer Oil," *15th Int. IEEE Pulsed Power Conference*, Monterey, CA, 13-17 June 2005.

2. M.D. Cevallos, M.D. Butcher, J.C. Dickens, A.A. Neuber, and H.G. Krompholz, "Composite Shadowgraphy and Luminosity Images of Self Breakdown Discharge Channels in Transformer Oil," *15th Int. IEEE Pulsed Power Conference*, Monterey, CA, 13-17 June 2005.

3. M. Butcher, M. Cevallos, A. Neuber, H. Krompholz, and J. Dickens, "Investigation of Charge Conduction and Self-Breakdown in Transformer Oil," *15th Int. IEEE Pulsed Power Conference*, Monterey, CA, 13-17 June 2005.

University of Missouri – Columbia

A. Journal Papers

1. K. S. Kelkar, N. E. Islam, C.M. Fessler, and W.C. Nunnally, "Design and characterization of silicon carbide photoconductive switches for high field applications,"Accepted JAP 2006

2. K. S. Kelkar, N. E. Islam, P. Kirawanich, C.M. Fessler, W.C. Nunnally, W. Kemp and A. Ashwani, "Effects of field dependent trapping and de-trapping on the responses of compensated GaAs photoconductive switches," (Under review IEEE transactions on plasma sciences)

3. K. S. Kelkar, N. E. Islam, C.M. Fessler, and W.C. Nunnally, "Transient response of the SI GaAs and SiC PCSS under high electric fields." (To be submitted August 2006.)

B. Papers in Conference Proceedings

1. K.S. Kelkar, W.C. Nunnally, N.E. Islam and C.M. Fessler, "Investigation of Optically Initiated Avalanche Silicon Carbide High Power Switches," International Power Modulator Conference, Washington, D.C., May 2006.

2. K.S. Kelkar, W.C. Nunnally, N.E. Islam and C.M. Fessler, "Investigation of Linear, Extrinsic Silicon Carbide Photo-Conductive Switch Materials," International Conference on plasma science, Michigan, June 2006.

3. W.C. Nunnally, N. Islam, J.E. Thompson, K.S. Kelkar, and C.M. Fessler, "Investigation of Extrinsic, Compensated, Semi-Insulating Silicon Carbide Photo-conductive Switches for Pulse Power Applications," US-Japan Symposium on Pulsed Power, Hawaii, August 2006.

NEW DISCOVERIES, INVENTIONS, OR PATENT DISCLOSURES

Patent disclosure: "Nanosecond Pulse Generator for Cell Electro-manipulation." USC File Number 3634.

HONORS/AWARDS